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The parallel lives of supermassive black holes and their host galaxies

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Summary. We compare all the available observational data on the redshift evolution of the total stellar mass and star formation rate density in the Universe with the mass and accretion rate density evolution of supermassive black holes, estimated from the hard X-ray selected luminosity function of quasars and active galactic nuclei (AGN). We find that on average black hole mass must have been higher at higher redshift for given spheroid stellar mass. Moreover, we find negative redshift evolution of the disk/irregulars to spheroid mass ratio. The total accretion efficiency is constrained to be between 0.06 and 0.12, depending on the exact value of the local SMBH mass density, and on the critical accretion rate below which radiatively inefficient accretion may take place.

1 Introduction

Observational evidence indicates that the mass of supermassive black holes (SMBH) is correlated with the luminosity (Marconi & Hunt, 2003 and references therein) and velocity dispersion (Tremaine et al., 2002 and references therein) of the host spheroids, suggesting that the process that leads to the formation of galaxies must be intimately linked to the growth of the central SMBH. Studying low redshift AGN, Heckman et al. (2004) have shown that not only does star formation directly trace AGN activity, but also that the sites of SMBH growth must have shifted to smaller masses at lower redshift, thus mimicking the "cosmic downsizing" scenario first put forward to describe galaxy evolution by Cowie et al. (1996). Such a scenario has recently received many independent confirmations, both for the evolution of SMBH as traced directly by X-ray and radio luminosity functions (LF) of AGN (Marconi et al. 2004; Merloni 2004; Hasinger et al. 2005), and for that of star forming galaxies, thanks to large surveys such as SDSS, GDDS, COMBO-17, GOODS, etc. (see, e.g. Heavens et al. 2004; Juneau et al. 2005; Pérez-González et al. 2005; Feulner et al. 2005).

Following Merloni, Rudnick and Di Matteo (2004; MRD04), here we discuss a *quantitative* approach to the study of the posited link between star formation and SMBH growth, based on a detailed comparison of the redshift evolution of integral quantities, such as the total stellar mass, black hole mass and star formation rate densities.

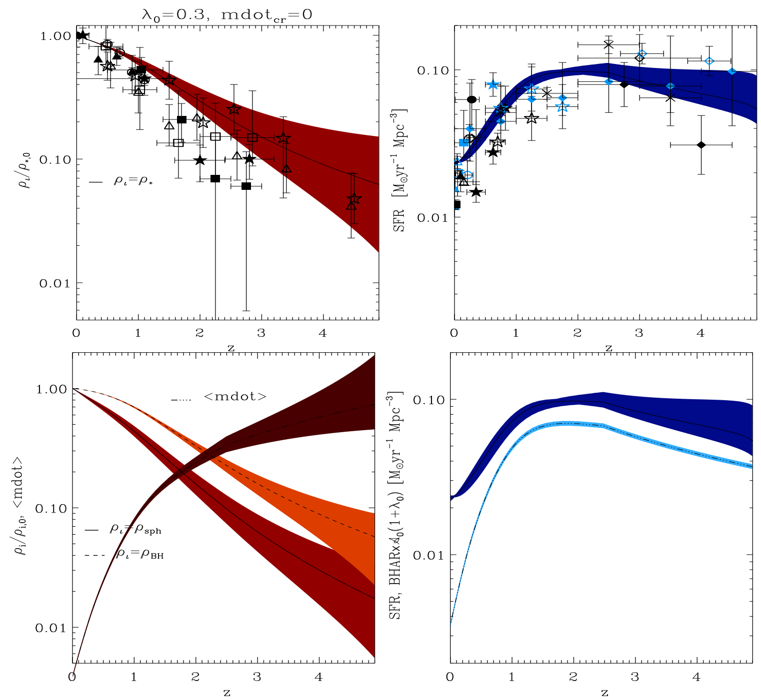

Fig. 1. The upper left panel shows the evolution of the stellar mass density as a function of redshift, where the density is given as a ratio to the local value, $\rho_{*,0} = 5.6 \times 10^8 M_\odot$ Mpc^{-3}, the upper right panel shows the SFR density. Our best-fit model is also shown in each panel. Values of $\lambda_0 = 0.3$ and $\rho_{\rm BH,0} = 2.5 \times 10^5 M_\odot$ Mpc^{-3} and $\dot{m}_{\rm cr} = 0$ are adopted here. Shaded areas represent 1-sigma confidence intervals of the model fits. The lower left panel shows a direct comparison between best-fit normalized mass density of spheroids (solid line, red shaded area) and black holes (dashed line, light red shaded area). Also shown is the evolution of the average Eddington scaled accretion rate $\dot{m}(z)$ (dotted line, dark red shaded area). Finally, the lower right panel shows a direct comparison between the best-fit SFR and BHAR (rescaled by a factor $\mathcal{A}_0(1+\lambda_0)$) densities.

2 SMBH as tracers of galaxy evolution

Under the standard assumption that black holes grow mainly by accretion, their cosmic evolution can be calculated from the luminosity function of AGN $\phi(L_{\rm bol}, z) = dN/dL_{\rm bol}$, where $L_{\rm bol} = \epsilon \dot{M} c^2$ is the bolometric luminosity produced by a SMBH accreting at a rate of $\dot{M}$ with a *radiative* efficiency ϵ (Soltan 1982). Following the discussion in MRD04, we will assume that the absorption corrected 2-10 keV luminosity function of AGN, $\phi(L_{\rm X}, z)$, (La Franca et al. 2005) best describes the evolution of the *entire* accreting black holes population, yielding:

$$\frac{\rho_{\rm BH}(z)}{\rho_{\rm BH,0}} = 1 - \int_0^z \frac{\Psi_{\rm BH}(z')}{\rho_{\rm BH,0}} \frac{dt}{dz'} dz', \qquad (1)$$

where the black hole accretion rate (BHAR) density is given by:

$$\Psi_{\rm BH}(z) = \int_0^\infty \frac{(1-\epsilon)L_{\rm bol}(L_{\rm X})}{\epsilon c^2} \phi(L_{\rm X}, z) dL_{\rm X} \qquad (2)$$

$L_{\rm X}$ is the X-ray luminosity in the rest-frame 2-10 keV band, and the bolometric correction function $L_{\rm bol}(L_{\rm X})$ is given by eq. (21) of Marconi et al. (2004). The exact shape of $\rho_{\rm BH}(z)$ and $\Psi_{\rm BH}(z)$ then depends only on the local black holes mass density $\rho_{\rm BH,0}$ and on the (average) radiative efficiency ϵ. This, in turn, is given by the product of the total accretion efficiency $\eta(a)$, itself a function of the inner boundary condition and thus of the black hole spin parameter a, and a function f of the Eddington scaled dimensionless accretion rate $\dot{m} \equiv L_{\rm bol}/L_{\rm Edd}$. Below a critical rate, $\dot{m}_{\rm cr}$, accretion does not proceed in the standard optically thick, geometrically thin fashion for which $\epsilon{=}\eta$. Its radiative efficiency, instead, critically depends on the nature of the flow: if powerful outflows/jets are capable of removing the excess energy which is not radiated, as, for example, in the ADIOS scenario (Blandford & Begelman 1999), then $f{=}1$, and black hole are always efficient radiators *with respect to the accreted mass* ("black holes are green!", Blandford 2005). On the other hand, if advection across the event horizon is the dominant process by which energy is disposed of (ADAF, Narayan & Yi 1995), we have:

$$\epsilon \equiv \epsilon(a, \dot{m}, \dot{m}_{\rm cr}) = \eta(a) f(\dot{m}, \dot{m}_{\rm cr}) = \eta(a) \begin{cases} 1, & \dot{m} \geq \dot{m}_{\rm cr} \\ \dot{m}/\dot{m}_{\rm cr}, & \dot{m} < \dot{m}_{\rm cr} \end{cases} \qquad (3)$$

We use the total BHAR and mass densities, $\Psi_{\rm BH}(z)$ and $\rho_{\rm BH}(z)$ respectively, to estimate the redshift evolution of the average global Eddington scaled accretion rate $\dot{m}(z) \propto \Psi_{\rm BH}(z)/\rho_{\rm BH}(z)$ (lower left panel of Fig. 1) and the corresponding radiative efficiency according to eq. (3). This allows us to identify the redshift at which a transition occurs in the global accretion mode of growing SMBH. Depending on the assumed value of $\dot{m}_{\rm cr}$, this transition redshift is 0, if black holes are always efficient accretors, i.e. $\dot{m}_{\rm cr} = 0$, or $z \approx 0.6$ if $\dot{m}_{\rm cr} \approx 0.05$. Given the overall evolution of the BHAR density, this also implies that radiatively inefficient accretion could contribute to only a small fraction of the total black hole mass density (see also Yu and Tremaine 2002; Merloni 2004; Hopkins et al. 2006 and references therein).

2.1 The parallel evolution

Our goal is to link the growth of SMBH from eq. (1) to the growth of stellar mass in galaxies. Because local SMBH are observed to correlate with spheroids only, we introduce the parameter $\lambda(z)$, the ratio of the mass in disks and irregulars to that in spheroids at any redshift, so that the total stellar

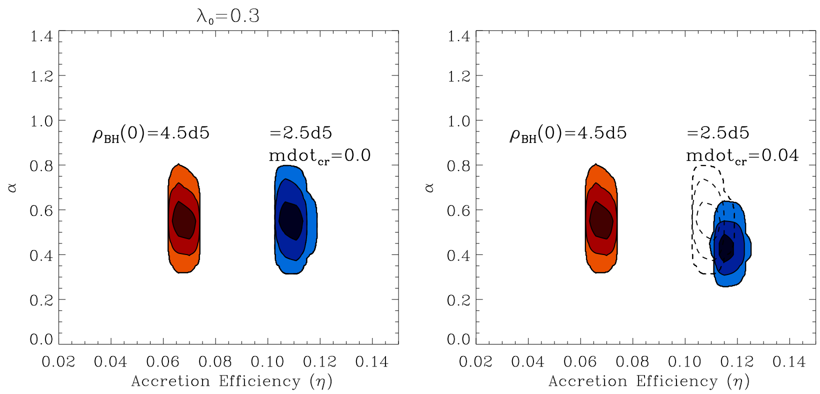

Fig. 2. 1,2 and 3 sigma confidence contours for the average accretion efficiency η and the index α describing the evolution of the stellar spheroid to black hole mass density ratio. In each panel, the leftmost and rightmost set of contours show the results obtained assuming $\rho_{\rm BH,0} = 4.5$ (Marconi et al. 2004), and $2.5 \times 10^5 M_\odot$ Mpc^{-3} (Yu and Tremaine 2002), respectively. Also shown is the dependence of such constraints on the assumed value of the critical rate between radiatively efficient and inefficient accretion (ADAF-like), with the dashed contours in the right panel showing the $\dot{m}_{\rm cr}$=0 reference point.

mass density can be expressed as: $\rho_*(z) = \rho_{\rm sph}(z) + \rho_{\rm disk+irr}(z) = \rho_{\rm sph}(z)[1 + \lambda(z)]$. We then assume that $\lambda(z)$ evolves according to $\lambda(z) = \lambda_0(1+z)^{-\beta}$, where λ_0 is the value of the disk to spheroid ratio in the local universe. Also we assume that the mass density of spheroids and supermassive black holes evolve in parallel, modulo a factor $(1+z)^{-\alpha}$, obtaining a prediction for the observable stellar mass density evolution as traced by SMBH growth:

$$\rho_*(z) = \mathcal{A}_0 \rho_{\rm BH}(\epsilon, z)(1+z)^{-\alpha}[1 + \lambda_0(1+z)^{-\beta}] \quad (4)$$

where $\mathcal{A}_0$ is the constant of proportionality in the Magorrian relation. By taking the derivative of (4), accounting for stellar mass loss, an expression is also found for the corresponding star formation rate (SFR) density evolution (see eq. (7) of MRD04).

With these expressions we obtain statistically acceptable simultaneous fits to all available observational data points (see MRD04 for a complete list of references) of both $\rho_*(z)$ and SFR(z). For each choice of $\rho_{\rm BH,0}$, λ_0, and of the critical accretion rate $\dot{m}_{\rm cr}$, the fitting functions depend only on three parameters: α, β and the accretion efficiency η. One example of such fits is shown in Fig. 1 for the specific case $\rho_{\rm BH,0} = 2.5 \times 10^5 M_\odot$ Mpc^{-3}, $\lambda_0 = 0.3$ and $\dot{m}_{\rm cr} = 0$. Because the drop in the AGN integrated luminosity density at low z is apparently faster than that in SFR density (see lower right panel of Fig. 1), the average black hole to spheroid mass ratio must evolve with lookback time ($\alpha > 0$; see lower left panel of Fig. 1). This result is independent from the local black hole mass density, or from λ_0, and is not strongly affected by the

choice of the value for the critical accretion rate. This is shown also in Fig. 2, where the constraints on the fit parameters are shown as confidence contours in the accretion efficiency–α plane for various choices of $\dot{m}_{\rm cr}$. As SMBH grow most of their mass at high $\dot{m}$, the global constraints on η are not strongly affected by any reasonable choice of $\dot{m}_{\rm cr}$.

3 Conclusions

We have made quantitative comparisons between the redshift evolution of the integrated stellar mass in galaxies and the mass density of SMBH. Although clearly correlated with the stellar mass density, SMBH accretion does not exactly track either the spheroid nor the total star assembly: irrespective of the exact mass budget in spheroids and disks + irregulars, the ratio of the total or spheroid stellar to black hole mass density was lower at higher redshift. Our results also suggest that the fraction of stars locked up into the non-spheroidal components of galaxies and in irregular galaxies should increase with increasing redshift ($\beta < 0$, see MRD04 for a discussion of this point). Our version of the Soltan argument yields a well defined constraint on the average radiative efficiency, and a corresponding one for the total accretion efficiency (i.e. on the mean mass-weighted SMBH spin), only weakly dependent on the uncertain physics of low $\dot{m}$ accretion flows.

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